International Journal of Engineering & Technology, 7 (4.39) (2018) 46-51

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Loss Analysis in Accordance Switching State of 3kW Full-bridge Converter with Current Doubler Rectifier

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Abstract

Background/Objectives: The losses mostly dissipate to the thermal and reduce the output efficiency of the power conversion system.
Methods/Statistical analysis: loss analysis of the 3kW DC-DC converter in accordance switching state through thermal module of circuit analysis tool.
Findings: Loss analysis of a DC-DC converter was performed using the thermal module function of circuit analysis tool. Loss of power semiconductor is analyzed by modeling power semiconductor device for loss analysis with device database editor.
Improvements/Applications: The thermal of power semiconductors analyzes the thermal by adding a thermal equivalent resistor to the device for power semiconductor loss analysis. The results are expected to be helpful for heat dissipation design. Future research will add inductor loss analysis.

Keywords: *DC-DC converter, Loss analysis, Thermal equivalent circuit, Thermal module*

1. Introduction

The full-bridge converter with a current doubler rectifier circuit is used for a DC-DC converter. The full-bridge circuit of the transformer primary side controls the duty ratio of the MOSFET switch through a phase-shift PWM generator. The MOSFET switch performs zero voltage switching with resonance due to the leakage inductance of the high frequency transformer and the parasitic capacitance of the MOSFET. The diode and the inductor of the transformer secondary side are rectified by double current rectification method[1-2].
The loss of the PS (Power Semiconductor) device is modeled by the thermal module function of the circuit analysis tool. The modeled device outputs the conduction losses and switching of each MOSFET and diode. The loss of power is increased with the switching frequency proportionally and most of this loss is caused by thermal. The thermal analysis of PS connects the thermal resistance to the outside of the analytical devices. The thermal resistance of PS outputs thermal of PS in proportion to the loss[3].
PS devices consist of MOSFETs and diodes. The loss of MOSFET and diode is distributed as conduction loss and switching loss. Switching losses in MOSFETs and switching losses in diodes account for most of the losses in high frequency applications. Because power loss affects power quality and efficiency, the task of estimating losses must be considered in the design of power conversion systems[4-7].
This research proposes the loss analysis of 3kW DC-DC converter using the thermal module function of circuit analysis. This method requires that the PS elements of the converter circuit be composed of elements for a simulation through the values given in the actual device data sheet. The simulation device uses the Device Data Base function of the circuit analysis tool to the input device information.

2. Loss Analysis of DC-DC Converter

2.1. DC-DC Converter Circuit

Figure 1 indicates the circuit of 3kW DC-DC full-bridge converter. The input AC power was rectified to DC through a bridge diode and the high frequency signal was filtered through an LC filter. The transformer primary circuit consisted of 4 MOSFETs connected in the form of a full bridge and controlled using the phase shift method. The secondary circuit of the transformer consisted of a diode current and a rectifier circuit that is suitable for a large power output using two inductors[1-2].

2.2. Switching state

2.2.1. Switching Signal

Figure 2 shows the waveform changes for one period on the transformer primary output voltage, current, and filter inductor output current when the MOSFET is switched by the phase shift control signal[1-2].

2.2.2. Operation Mode

Figure 3 indicates the operation circuit of each section of DC-DC converter according to switching state of MOSFET[1-2].
Operation Mode 1 [t_0~t_1]:S_1, and S_4 are in the conducting state, and primary side voltage,V_p, is equal to input voltage,V_{dc}.

$$V_p = V_{dc}, i_p(t) = \mathrm{n} i_{L1}(t) \quad (1)$$

The input energy is transmitted to doubler current rectifier circuit by S_1 and S_4.The delivered power is flowed to the load side through inductor,L_1, output capacitor,C_o, and diode,D_2. D_1 is in the off state because inductor current, i_{L2}, flows through inductor, L_2, and output capacitor, C_o. Mode 1 endswhen the switch,S_4, is in off state. The output current in mode 1 and the current in filter inductors,L_1 and $L_2$are as follows:

$$i_o(t) = i_{L1}(t) + i_{L2}(t) \tag{2}$$

$$i_{L1}(t) = i_{L1}(t_0) + \frac{nV_{dc}-V_o}{L_1}(t - t_0) \tag{3}$$

$$i_{L2}(t) = i_{L2}(t_0) - \frac{V_o}{L_2}(t - t_0) \tag{4}$$

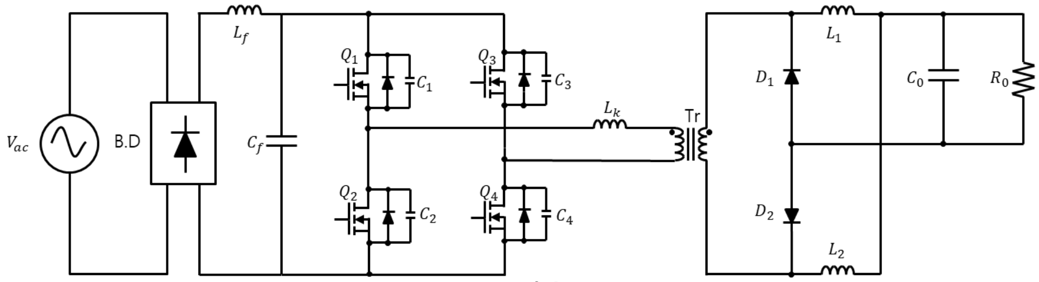


Figure 1: Circuit structure of 3kW DC-DC converter

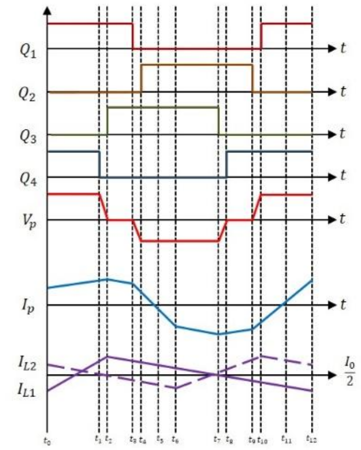
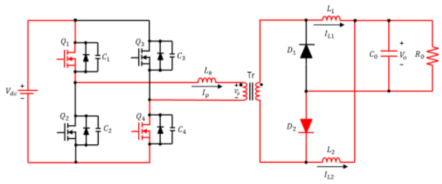
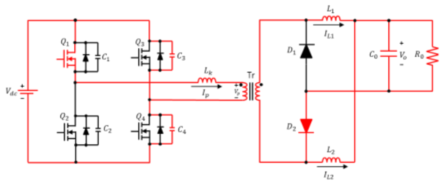


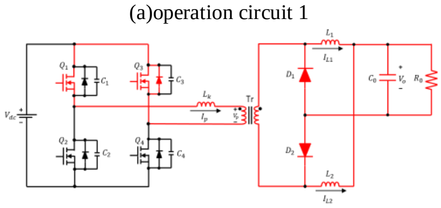
Figure 2: Circuit for each operation section of a DC-DC converter



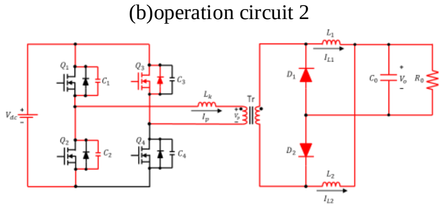
(a)operation circuit 1



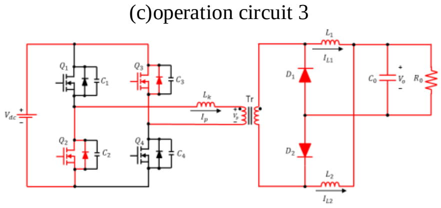
(b)operation circuit 2



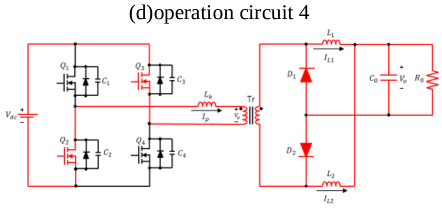
(c)operation circuit 3



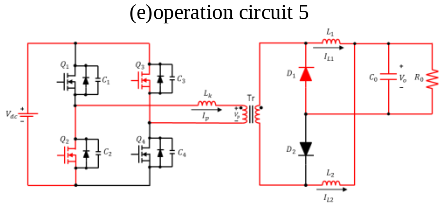
(d)operation circuit 4



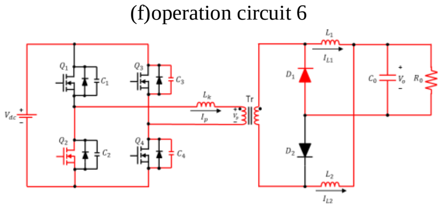
(e)operation circuit 5



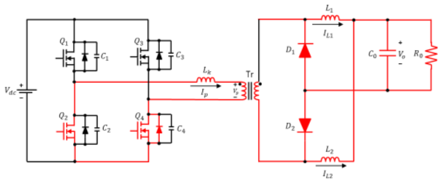
(f)operation circuit 6



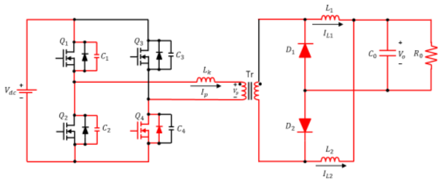
(g)operation circuit 7



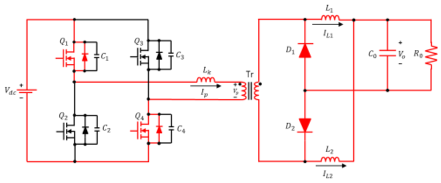
(h)operation circuit 8



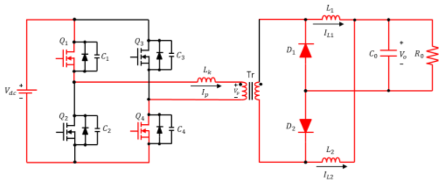
(i)operation circuit 9



(j)operation circuit 10



(k)operation circuit 11



(l)operation circuit 12

Figure 3: Operation circuit for each mode

Operation Mode 2 [t_1~t_2]: At time t_1, S_4 is turned off, output capacitance,C_4, of S_4 is charged to V_{dc}, and output capacitance,C_3. $S_3$is discharged at a zero voltage switching(ZVS).

$$C_{eq} = C_3 + C_4 = 2C_{oss}(C_{oss} = C_1 = C_2 = C_3 = C_4) \quad (5)$$

The voltages of the switch output capacitances,C_3 and C_4, are as follows:

$$V_{C3}(t) = V_{dc} - \frac{ni_{L1}(t_1)}{2C_{oss}}(t - t_1) \quad (6)$$

$$V_{C4}(t) = \frac{ni_{L1}(t_1)}{2C_{oss}}(t - t_1) \quad (7)$$

The currents and voltages of the transformer primary and secondary side, output current, and inductors L_1 and L_2 are as follows:

$$V_p \cong V_{dc} - V_{C4}(t) \quad (8)$$

$$i_p(t) = ni_{L1}(t) \quad (9)$$

$$i_o = i_{L1}(t) + i_{L2}(t) \quad (10)$$

$$i_{L1}(t) = i_{L1}(t_1) + \frac{nV_{dc} - V_o}{L_1}(t - t_1) \quad (11)$$

$$i_{L2}(t) = i_{L2}(t_1) - \frac{V_o}{L_2}(t - t_1) \quad (12)$$

The time of mode 2 can be expressed as

$$\Delta t_{1\sim 2} = \frac{V_{dc}}{ni_{L1}(t_1)}2C_{oss} \quad (13)$$

Operation Mode 3 [t_2~t_3]: At time t_2, output capacitor,C_3, discharges to zero voltage because diode of switch S_3 is conducting, and S_3 is in a conducting state under the ZVS operation. To ensure the ZVS, the delay time,t_d, is required between S_4 and S_3 switching times. The required delay t_d is as follows:

$$t_d \cong \frac{4C_{oss}V_{dc}}{ni_{L1}(t_1)} \approx 2\Delta t_{12} \quad (14)$$

The transformer primary and secondary voltages are zero.

$$V_p \cong V_{s,drop} \cong 0 \quad (15)$$

In equation (15), $V_{s,drop}$ is the voltage drop of the diodes. The secondary side diodes D_1 and D_2 are turn-on, and the current of L_1,L_2,$i_p$is equation (16-18).

$$i_{L1}(t) = i_{L1}(t_2) - \frac{V_o}{L_1}(t - t_2) \quad (16)$$

$$i_{L2}(t) = i_{L2}(t_2) - \frac{V_o}{L_2}(t - t_2) \quad (17)$$

$$i_p(t) \cong \left[i_p(t_2) + \frac{V_{s,drop}}{r}\right] e^{-\frac{r}{L_k}(t-t_2)} - \frac{V_{s,drop}}{r} \quad (18)$$

In equation (18), r is the equivalent series resistance to leakage inductance, and mode 3 ends when switch S_1 is turned off.

Operation Mode 4 [t_3~t_4]: At time t_3, S_1 is in the off state because the energy stored in leakage inductor is discharged through C_1. $C_1$is charged up to V_{in}, and the C_2 is discharged with the zero voltageas follows:

$$V_{C1}(t) = \frac{1}{C_{eq}}\int_{t_3}^{t} i_p(\tau)d\tau \cong \frac{i_p(t_3)}{2C_{oss}}(t - t_3) \quad (19)$$

$$V_{C2}(t) = V_{dc} - \frac{1}{2C_{oss}}\int_{t_3}^{t} i_p(\tau)d\tau \cong V_{dc} - \frac{i_p(t_3)}{2C_{oss}}(t - t_3) \quad (20)$$

The voltage and current at both end of the transformer are as follows:

$$V_p(t) = -V_{C1}(t) \quad (21)$$

$$i_p(t) \approx \left[i_p(t_3) + \frac{V_{C1}(t)}{r}\right] e^{-\frac{r}{L_k}(t-t_3)} - \frac{V_{C1}(t)}{r} \quad (22)$$

$$i_{L1}(t) = i_{L1}(t_3) - \frac{V_o}{L_1}(t - t_3) \quad (23)$$

$$i_{L2}(t) = i_{L2}(t_3) - \frac{V_o}{L_2}(t - t_3) \quad (24)$$

The time of the mode 4 is as follows:

$$\Delta t_{3\sim 4} = \frac{V_{dc}}{i_p(t_3)}2C_{oss} \quad (25)$$

Operation Mode 5 [t4-t5]: At time t_4, C_2 is discharged to zero voltage because the diode ofS_2 is turn-on. Therefore, S_2 is turn-on in zero voltage. The voltage of primary side is $V_p = -V_{dc}$.To ensure the ZVS of S_2, a delay time,t_d, is required between $S_{1(off)}$ and $S_{2(on)}$, and the delay time $t_d$can be expressed as

$$t_d = \frac{4C_{oss}V_{dc}}{ni_{L1}(t_3)} \approx 2\Delta t_{34} \quad (26)$$

When the primary current,i_p, becomes 0, the voltage is terminated and the voltage and the current of L_1 and $L_2$are as follows:

$$V_p = -V_{dc} \quad (27)$$

$$i_p(t) = i_p(t_4) - \frac{V_{dc}}{L_k}(t - t_4) \quad (28)$$

$$i_{L1}(t) = i_{L1}(t_4) - \frac{V_o}{L_1}(t - t_4) \quad (29)$$

$$i_{L2}(t) = i_{L2}(t_4) - \frac{V_o}{L_2}(t - t_4) \quad (30)$$

Operation Mode 6 $[t_5 \sim t_6]$: Operation circuit 6 is similar to operation circuit 5 except that the input current, i_p, is negative and the diodes of S_2 and S_3 are turn-off. The current of L_1amdL_2 is as follows:

$$V_p = -V_{dc} \quad (31)$$

$$i_p(t) = -\frac{V_{dc}}{L_k}(t - t_5) \quad (32)$$

$$i_{L1}(t) = i_{L1}(t_5) - \frac{V_o}{L_1}(t - t_5) \quad (33)$$

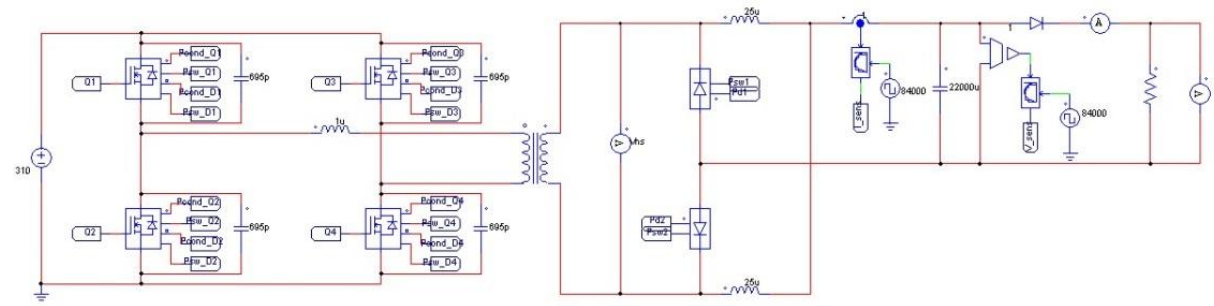
$$i_{L2}(t) = i_{L2}(t_5) - \frac{V_o}{L_2}(t - t_5) \quad (34)$$

Operation Mode 1 to Operation Mode 6 and Operation Mode 7 to Operation Mode 12 are symmetrical modes. The twelve modes of operation are interpreted differently depending on the states of the four switches and the two diodes. One cycle is formed through twelve different operations, and the ZVS operation can be confirmed.

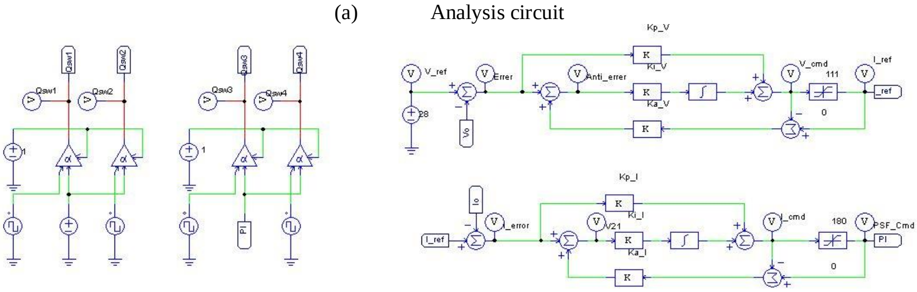
2.3. Loss Analysis

Figure 4 shows the simulation circuit for a 3kW-class full-bridge DC-DC converter considering the practical converter behavior. Table 1 lists the specifications of the converter. Table 2 lists a description of each element of the circuit for loss analysis of the MOSFET[1-2].

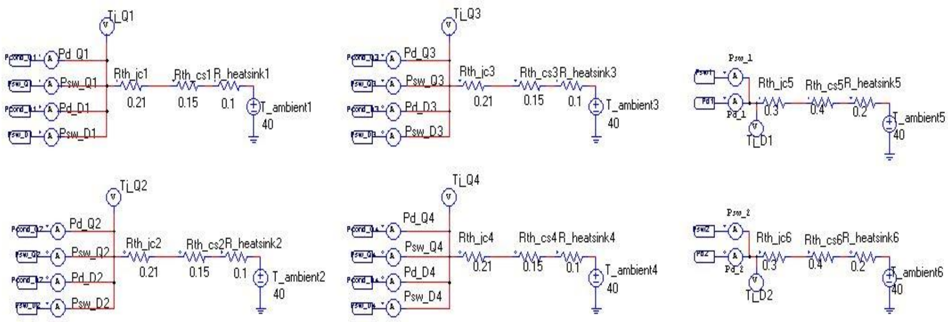
Figure 5 presents the input values of the data sheet parameters of IXFK24N100F MOSFET using the Device Database Editor provided in Thermal Module of circuit analysis tool[3-5].



(a) Analysis circuit



(b) Control circuit



(c) Thermal equivalent circuit

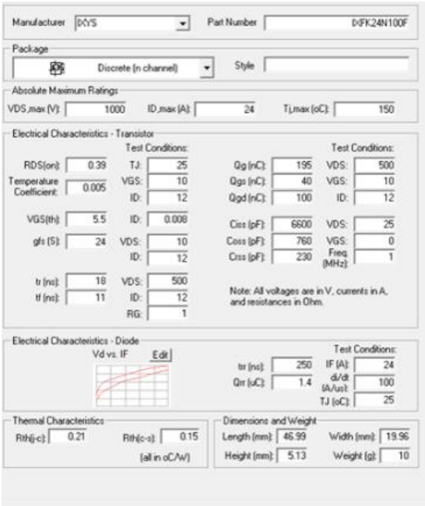
Figure 4: DC-DC converter analysis circuit

Table 1: Simulation Specifications

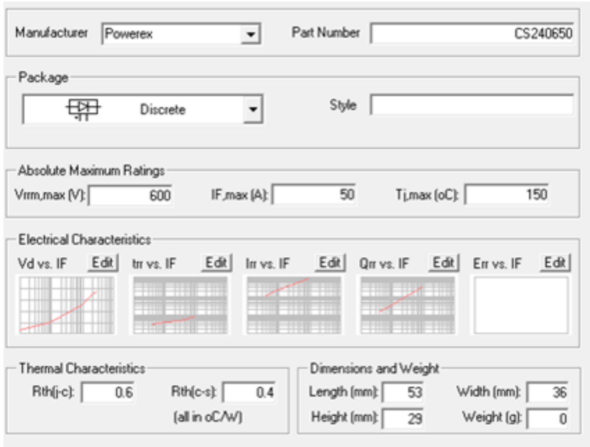
Parameter	Value	Unit	Parameter	Value	Unit
Input voltage	310	V_{dc}	Leakage inductance	3.6	μH
Output voltage	28	V_{dc}	Output inductor	25	μH
Output current	111	A	Output capacitor	22,000	μF
MOSFET	IXYS24N100F		Switching frequency	84	kHz
Fast Recovery Diode	CS240650				

Table 2: Thermal equivalent circuit

Parameter	Explanation	Unit
$R_{th(j-c)}$	MOSFET's thermal resistance between Junction to Case	Ω
$R_{th(c-s)}$	MOSFET's thermal resistance between Case to Heatsink	Ω
$R_{heatsink}$	thermal resistance of heat sink	Ω
$T_{ambient}$	Atmospheric temperature conditions	V_{dc}



(a) IXFK24N100F



(b) CS240650

Figure 5: Device database editor

3. Results and Discussion

3.1. Loss Equation

The loss of DC-DC converter with high switching frequency is caused mostly by the switching of PS device and the remainder is generated by conduction. Therefore, the switching loss and conduction loss of MOSFET and diode in PS devices of DC-DC converter are studied[6-7].

The conduction loss of a MOSFET occurs when the current flows when the MOSFET is turned on and the internal resistance of the MOSFET, is expressed as equation (35).

$$P_{cond(MOSFET)} = I_{drain}^2 \times R_{DS(on)} \quad (35)$$

where I_{drian} is drain current of MOSFET and $R_{DS(on)}$ is internal resistance between drain and source of MOSFET.

The switching loss of MOSFET is the loss that occurs when switch is turned on and off. This is the loss caused by the overlap between the voltage and current flowing between drain and source of the MOSFET. Therefore, the switching loss is expressed as equation (36).

$$P_{sw(MOSFET)} = (E_{on} + E_{off}) \times f_{sw} \quad (36)$$

where $E_{on} and E_{off}$ are the energy losses when the MOSFET is turned on and off, f_{sw} is switching frequency, V_{DS} is voltage of between drain and source, and I_{drain} is drain current.

The conduction loss of a diode is caused by the voltage drop occurring during conduction and is expressed as equation (37).

$$P_{cond(Diode)} = V_d \times I_d \quad (37)$$

where V_d is the voltage drop of diode and I_d is forwardcurrent of diode.

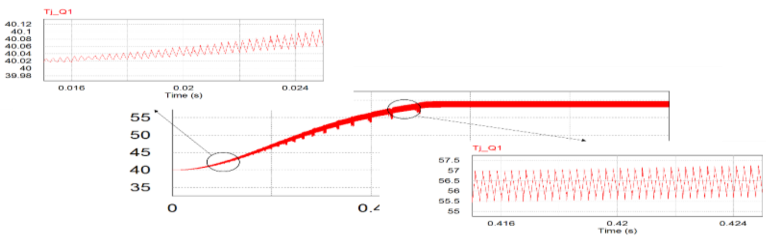
The switching loss of the diode is the loss caused by the reverse recovery current during turn off and is expressed as equation (38).

$$P_{trr(Diode)} = E_{rr} \times f_{sw} \frac{V_r}{V_{r(datas\square eet)}} \quad (38)$$

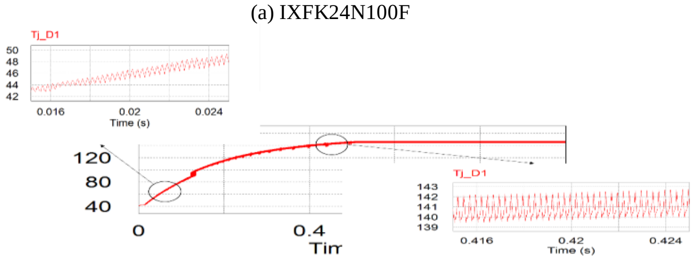
where E_{rr} is energy loss of reverse recovery, V_r is the reverse blocking voltage, $V_{r(datasheet)}$ is the reverse blocking voltage in the Err characteristics of the datasheet, Q_{rr} is the reverse recovery charge, t_{rr} is the reverse recovery time, and I_{rr} is peak the reverse recovery current.

3.2. Loss Analysis Result

Figure 6(a) shows the simulation result showing the total loss of the MOSFET, and Figure 6(b) presents the simulation result showing the total loss of the diode.



(a) IXFK24N100F



(b) CS240650

Figure 6: Lose analysis result

4. Conclusion

Loss analysis of a DC-DC converter was performed using the thermal module function of circuit analysis tool. Loss of PS is analyzed by modeling PS device for loss analysis with device database editor. The thermal of PSs analyzes the thermal by adding a thermal equivalent resistor to the device for PS loss analysis. The results are expected to be helpful for heat dissipation design. Future research will add inductor loss analysis.

Acknowledgment

This work was supported by KEPCO Research Institute grant funded by Korea Electric Power Corporation (R16DA11) and NRF-2017R1A2B1009684

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